A1199
Are We Alone?
The Search for Life in the Universe
Summer 2019

Instructor: Shami Chatterjee

Note: HW 1 posted.
So far: Measuring the Universe
Next: Olbers’ Paradox and The Big Bang
The Search for Life in the Universe

What the course is about:

• Where, when, and how we may find life elsewhere.
• Three big words:

  **Universe:**
  The big picture, fundamentals, profound facts.

  **Life:**
  Is finding bacteria as good as finding counterparts to us?

  **Search:**
  How will we find, detect, or infer life elsewhere?
  Space probes vs. remote sensing.
Inverse-Square Laws

Area of a sphere $= 4\pi R^2$.

Conservation of flux (of whatever) implies that it must scale as:

$$F(R) \sim \frac{1}{R^2}.$$ 

Works for gravity, electric field, magnetic field, flux of light from a light bulb or a star, etc., etc.

= Very general principle.
Distances from Luminosities

\[ F_{c1} = \frac{L_0}{(4\pi D_1^2)} \]

\[ F_{c2} = \frac{L_0}{(4\pi D_2^2)} \]

\[ D_1 = 2D_2 \]

\[ F_{c1} = \frac{1}{2^2} F_{c2} = \frac{1}{4} F_{c2}. \]

Hertzsprung-Russell diagram, illustrating stellar surface temperature, color, and absolute luminosity.

If we can classify a star (based on color, spectral lines) we can (very approximately) infer its distance.
Cepheids and Other Distance Indicators

Cepheid variables:
- Very luminous stars that pulsate in a regular cycle.
- Rapid brightening followed by gradual dimming.
- Named after delta Cephei, a naked eye star, the first of this type to be identified.
- “Eddington valve”.
- Rare, but key to the distance ladder:

\[ M = -2.78 \log (P) - 1.35 \]

**The absolute brightness and the pulsation period are related:**

M: absolute magnitude;
P: period in days.
Doppler Shifts

Change in apparent wavelength (and pitch) due to relative motion of source and detector.

\[ \frac{\Delta \lambda}{\lambda} = \frac{v}{c} \]
Spectral lines

Interaction between a quantum system and a single photon:
Photons absorbed or emitted at very specific wavelengths.

Emission spectrum
Absorption spectrum
White light

Lines can be broadened by many phenomena:
e.g., collisions, magnetic field effects, thermal Doppler broadening, etc.

Lines provide a fingerprint to identify emitting or absorbing material.
Spectral lines
What is happening here?

The Doppler shift of spectral lines (emission or absorption) traces the velocity of the emitting or absorbing material, according to our Doppler shift equation, $\Delta \lambda / \lambda = v/c$. 
So far…

- The radius of the Earth (6400 km).
- The Earth-Sun distance (1 AU = 150 million km).
- The speed of light ($3 \times 10^8$ m/s or 300,000 km/s).
- Parallax: model-independent distances.
- Inverse-square laws: $F(R) \sim 1/R^2$.
- Distances from Cepheids.
- Doppler shifts, $\Delta \lambda / \lambda = v/c$.
- Spectral lines.
Redshift and Cosmological Expansion

In 1923, Hubble identified Cepheid variable stars in the Andromeda galaxy. P=31.45 days → 7000 times brighter than Sun. Implied that Andromeda was 300 kpc away.

Follow-up: Distances to many other galaxies…

(Velocities from Doppler shifts of spectral lines; Distances from Cepheids.)

Edwin Hubble observing at the 100-inch telescope at Mt. Wilson, early 1920s.
In spite of many systematic errors, the basic trend is clear:

Galaxies that are further away are moving away from us faster.

“A relation between distance and radial velocity among extra-galactic nebulae”
- E. Hubble (1929)
Why is the Night Sky Dark?

On a moonless night: night sky $< 10^{-6}$ daytime brightness.

“It takes a genius to realize that the relative weakness of starlight is of great cosmological significance, and such a person was Johannes Kepler.”

(E. R. Harrison, *Cosmology*).
Why is the sky dark at night?
(Heinrich Olbers, 1823)

If the universe were infinite, then every line of sight would eventually intercept a star (or galaxy) and hence the whole night sky should look like the surface of a star.

Remember: the concept of “galaxy” is < 100 years old.
Olbers’ paradox

Olber (1784-1840)
Infinite or Finite Universe?

# of stars \( \propto R^2 \)

\[ \Delta V = 4 \pi R^2 \Delta R \]

4X as many stars

9X as many stars

https://i.ytimg.com/vi/GGPEEU5CSIY/hqdefault.jpg
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Possible answers:

2. Olbers 1823: universe infinite but starlight is absorbed by intervening material.
3. Poe 1848: ‘… by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all.’
4. 20th century: redshifts make distant objects dim at a given wavelength: Hubble law.

Who is correct?
Olbers’ Paradox

Why is the sky dark at night? (Heinrich Olbers, 1823)

If the universe were infinite, then every line of sight would eventually intercept a star (or galaxy) and hence the whole night sky should look like the surface of a star.

Solution: universe must be finite in space, in age, or both.
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Who is correct? Poe.

Because: (1) The speed of light is finite ($3 \times 10^5$ km/s).
(2) The universe has finite age.
Life in the Universe

- What type of universe do we live in?
- What are its properties?
- Is life an accident or inevitable in a universe like ours?
- How does the timeline of the cosmos inform us about the prevalence of life elsewhere?
  - Bacterial life?
  - Intelligent life?
  - Technological civilizations?
Cosmological Context

We need the ultimate context for discussing our origins.

• Are we typical or not?
  – What does “typical” mean?

• If we are a rare fluke, there is no reason to search for life elsewhere!

• What do we mean by “we?”
  – Homo sapiens only?
  – Microbes predominantly?

• Given that we are curious and would like to find life elsewhere, how does cosmology, astrophysics and biology guide us on where to look?
Cosmological Context

Why do we find ourselves in this universe?

• Initiated 13.7 Gyr ago in a hot big bang.
• 3 + 1 dimensions.
• These physical laws and fundamental constants.
• 96% of the universe is filled with stuff that we don’t understand (dark matter, dark energy).
• Complexity: galaxy clusters, stars, planets, life on at least one planet.
COSMOLOGY MARCHES ON

WHERE THE HELL DID IT ALL COME FROM?

WHERE THE HELL DID IT ALL COME FROM?
Cosmological Context

As far as we know, it doesn’t have to be this way!

• There may be other universes with entirely different properties.

• We find ourselves in this one because it has the right properties to produce us.
  – Is this statement profound or obvious?
  – Described as the “anthropic principle”.


Fundamental Observations

• The night sky is dark. (Olbers’ paradox; the universe must be finite in size and age.)

• There have been no obvious visitations from extraterrestrials (microbes or aliens).

• The Earth and the solar system are middle-aged: 4.6 Gyr vs. ~12 Gyr (MW) vs. 13.7 Gyr (U).
Fundamental Observations

The laws of physics:

• **The good news:** can extrapolate back to <<1 sec after Big Bang ... for describing matter and radiation.

• **The bad news:**
  • Matter is only 4% of the universe.
  • The structure of the universe was largely determined by physics that goes beyond our ability to extrapolate backwards – the action was at $10^{-43}$ sec (the Planck time).
Looking back to the dawn of time

UNDERSTANDING THE BIG BANG
The Pillars of the Big Bang

• Hubble Expansion.
• The Cosmic Microwave Background.
• Elemental Abundances.
Redshift and Cosmological Expansion

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\[ V = H_0 \times D \]

- \( V \): Recession velocity, from Doppler shift of spectral lines.
- \( D \): Distance, as estimated using distance ladder.
- \( H_0 \): The “Hubble constant”.
Trouble with the Hubble Constant

- Hubble Expansion:
  \[ V = H_0 D, \text{ with } H_0 = \ldots \? \]

This is not an easy measurement to make!
Systematic errors are hard to calibrate out.

(https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/)
The Hubble Space Telescope

Launched 1990, on the space shuttle Discovery.

Low earth orbit, about 350 miles up.

2.4-m mirror; diverse suite of instruments.

Service missions to install corrective optics, upgrade instruments; 5 visits; last in 2009.
Distance to the Virgo cluster galaxy M100 from Hubble Space Telescope observations of Cepheids


NATURE • VOL 371 • 27 OCTOBER 1994

Accurate distances to galaxies are critical for determining the present expansion rate of the Universe or Hubble constant ($H_0$). An important step in resolving the current uncertainty in $H_0$ is the measurement of the distance to the Virgo cluster of galaxies. New observations using the Hubble Space Telescope yield a distance of $17.1 \pm 1.8$ Mpc to the Virgo cluster galaxy M100. This distance leads to a value of $H_0 = 80 \pm 17$ km s$^{-1}$ Mpc$^{-1}$. A comparable value of $H_0$ is also derived from the Coma cluster using independent estimates of its distance ratio relative to the Virgo cluster.

Hubble Space Telescope “Key Project” on the extragalactic distance scale: provide a measure of the Hubble constant accurate to 10%.
The Pillars of the Big Bang

• Hubble Expansion.
  \[ V = H_0 \cdot D, \text{ with } H_0 = 72 \text{ km/s/Mpc}. \]

• The Cosmic Microwave Background.

• Elemental Abundances.
The Cosmic Microwave Background

• The early universe was hot and dense.
• As it expanded rapidly, it cooled – radiation from that early epoch should still be visible in the microwave band.
• “Relic radiation”.

Serendipitous discovery by Penzias and Wilson, 1964. (Nobel prize in 1978.)

• Isotropic, uniform, black-body radiation at 2.73 K.
The Cosmic Microwave Background

• The CMB is isotropic and uniform – the Big Bang happened “everywhere”.

• Essentially perfect black body radiation, $T = 2.72548 \pm 0.00057$ K (peak at 160 GHz or 1 mm).
The Cosmic Microwave Background

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- Earth’s orbit around Sun: subtract Doppler shift.

- Milky way: subtract local structure.
The Cosmic Microwave Background

Wilkinson Microwave Anisotropy Probe (WMAP) 9-year data: 13.77 billion year old temperature fluctuations → the seeds that grew to become galaxies.
Plot temperature range is ± 200 microKelvin.
Our galaxy signature was subtracted using multi-frequency data.
The Cosmic Microwave Background

Small fluctuations in the CMB (after subtracting uniform component) at the surface of last scattering.

Fluctuations are $\sim 200$ microKelvin on 2.73 K background.

Seeds for structure formation – galaxies and galaxy clusters.

We can only see the surface of the cloud where light was last scattered.

The cosmic microwave background radiation’s “surface of last scatter” is analogous to the light coming through the clouds to our eye on a cloudy day.
The Pillars of the Big Bang

• Hubble Expansion.
  \[ V = H_0 \cdot D, \text{ with } H_0 = 72 \text{ km/s/Mpc}. \]

• The Cosmic Microwave Background.
  Uniform, isotropic, 2.73 K black body radiation, with \(~20\) microK fluctuations.

• Elemental Abundances.